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An overview of utilizing water-in-diesel emulsion fuel in diesel engine and its potential research study

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A B S T R A C T

The need for more efficient energy usage and a less polluted environment are the prominent research areas that are currently being investigated by many researchers worldwide. Water-in-diesel emulsion fuel (W/D) is a promising alternative fuel that could fulfills such requests in that it can improve the combustion efficiency of a diesel engine and reduce harmful exhaust emission, especially nitrogen oxides (NO_x) and particulate matter (PM). To date, there have been many W/D emulsion fuel studies, especially regarding performance, emissions and micro-explosion phenomena. This review paper gathers and discusses the recent advances in emulsion fuel studies in respect of the impact of W/D emulsion fuel on the performance and emission of diesel engines, micro-explosion phenomena especially the factors that affecting the onset and strength of micro-explosion process, and proposed potential research area in W/D emulsion fuel study. There is an inconsistency in the results reported from previous studies especially for the thermal efficiency, brake power, torque and specific fuel consumption. However, it is agreed by most of the studies that W/D does result in an improvement in these measurements when the total amount of diesel fuel in the emulsion is compared with that of the neat diesel fuel. NO_x and PM exhaust gas emissions are greatly reduced by using the W/D emulsion fuel. Unburnt hydrocarbon (UHC) and carbon monoxide (CO) exhaust emissions are found to be increased by using the W/D emulsion fuel. The inconsistency of the experimental result can be related to the effects of the onset and the strength of the micro-explosion process. The factors that affect these measurements consist of the size of the dispersed water particle, droplet size of the emulsion, water-content in the emulsion, ambient temperature, ambient pressure, type and percentage of surfactant, type of diesel engine and engine operating conditions. Durability testing and developing the fuel production device that requires no/less surfactant are the potential research area that can be explored in future.

1. Introduction

The rise in sea level, shrinking snow cover and ice sheet, retreat of glaciers as well as the current extreme weather like severe droughts and flooding, are due to the effects of climate change. Over 90% of the causes of the climate change come from human activities [1] of which the biggest cause of this catastrophe is contributed from atmospheric emission, especially gasses and aerosols that are being stored in the atmosphere. These gasses are known as greenhouse gasses. The largest growth in their emission has come from fossil fuel combustion, representing 57% of the total greenhouse gasses, which is largely produced from the emissions from industry and transportation [2]. Industrial and transportation emissions are not only harmful to the environment, but are also hazardous to our health, especially nitrogen oxides (NO_x) and particulate matter (PM) gas emissions. The effects of these hazardous emissions include serious damage to our health. Lung

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cancer, asthma, cardiovascular issues and other fatal illness that would cause premature death are among the effects of such harmful emissions. Due to the severe environmental issues that the world is facing recently, new emission regulations are constantly being introduced in order to mitigate this problem. The Kyoto Protocol, which was established in 1997, was the first step to set binding obligations on industrialized countries to reduce their emissions. In addition to environmental disputes, the issue of critical fossil fuel reserves is another concern. Some studies estimate that the worldwide fossil fuel reserves will last less than four decades [3]. Accordingly, these two serious issues have generated research interest worldwide in order to curb and find a solution to these problems. Currently, the more efficient utilization of energy and less polluting emissions are the prominent research areas that are progressively being studied [4–6].

The compression ignition engine, or so called diesel engine, is the favored source of power for heavy industrial and transportation compared to the spark ignition engine, otherwise known as the gasoline engine, due to its high power output and fuel economy [7]. Nonetheless, diesel engines emit more hazardous emissions, especially NO_x and PM. Due to the stringent emission regulations that have been implemented, many devices are being invented in order to reduce these exhaust gas emissions. Devices like NO_x Absorber Catalysts (NAC) and Selective Catalytic Reduction (SCR) are able to reduce the formation of NO_x to a large extent. Furthermore, Diesel Oxidation Catalysts (DOCs) and Diesel Particulate Filters (DPFs) are devices commonly used for the reduction of PM. DOCs are an inexpensive, robust device that are suitable for non-road applications and are capable of reducing PM to 25% or more. As for DPFs, they are able to reduce the formation of PM by up to 90% and work effectively on engines that are able to sustain high exhaust temperature. However, the cost is three times more expensive than DOCs [8]. Nevertheless, the techniques that are used to reduce NO_x, lead to an increase in smoke and PM and vice versa [9]. In addition, they tend to increase the fuel consumption of the engine [10]. It is difficult to simultaneously reduce both NO_x and PM, and, at the same time, maintain or improve the performance of the engine.

The introduction of water into the diesel engine is a promising method that can reduce the formation of NO_x and PM emissions simultaneously [11,12]. There are three common methods to introduce water into the engine: spraying water into the intake manifold, which is called intake manifold fumigation [13–15]; water injection into the combustion chamber or so called direct water injection [16,17]; and water-in-diesel emulsion fuel (W/D). The intake manifold fumigation uses the combination of a valve and flow meter to control the water flow rate. It is claimed to reduce the NO_x as a result of the presumable uniform water vapor in the cylinder at the time of combustion. The vaporization of the water process arises from the time the air and water are heated through the compression stroke [11]. As for the direct water injection method, the water is injected into the combustion chamber in a separate unit or injector. It can reduce NO_x more than the fumigation method due to the water droplets being closer to the flame during the combustion. In addition, the presence of water in the fuel spray increases the penetration of the fuel (liquid and vapor) during the spray period [7]. However, both the intake manifold fumigation and direct water injection method lead to an increase in the formation of hydrocarbon (HC) and emission of carbon monoxide (CO) [18,19]. Furthermore, as the water is introduced into the combustion chamber, it tends to be in direct contact with the fuel feed system and cylinder-piston group, thus resulting in oil contamination and increasing wear [18]. In addition, both methods require highly complex engine modification in order to integrate the water addition device to the engine. Thus, it requires high additional cost [20].

W/D emulsion fuel is the promising alternative fuel that can reduce NO_x and PM emission simultaneously while at the same time improving the combustion efficiency [9,12,21,22]. Moreover, the usage of W/D emulsion fuel does not require any modification of the engine [22]. W/D emulsion fuel is the potential alternative fuel that could contribute the world's needs: more efficient energy usage and less polluting emission. To date, many aspects of W/D emulsion fuel studies have been conducted, especially regarding diesel engine performance and the emission of diesel engines utilizing the aforementioned fuel. In addition, a few review papers have been published regarding the alternative fuel, reporting the positive effects it gives to an engine's performance and emission, discussing combustion characteristic inside the combustion chamber as well as the micro-explosion phenomena which is a special occurrence that intrigues researchers worldwide as it is nonexistent in the normal diesel combustion process in a diesel engine [7,21–23]. However, there are a lot of inconsistent findings being revealed from the W/D emulsion fuel studies especially on the engine performance result since there are a lot of parameters that can influence the effectiveness of the fuel. Less effort has been shown to reveal and discuss the cavities and issues involved when utilizing the aforementioned fuel. Therefore, a new review paper is needed to discuss the issues in details and also propose potential research area that would give contribution to the W/D emulsion fuel study in the future.

This review paper gathers and discusses the recent advance of W/D emulsion fuel studies especially the impact of using W/D emulsion fuel to the performance and emissions of engine. Studies revealed that the onset and the strength of micro-explosion process give strong effect with regards to the combustion efficiency inside the combustion chamber [24,25]. These two elements in micro-explosion process may have strong relation to the inconsistency result that stated earlier. In relation to that, the factors that affect the onset and the strength of the micro-explosion process are investigated in details. Other than that, the surfactant, emulsion fuel stability and types of emulsion fuel are also being reviewed in details. In addition, the paper also recommends the potential research areas regarding the W/D emulsion fuel that seldom being explored.

2. Water-in-diesel emulsion fuel

The term emulsion is defined as a mixture of two or more immiscible liquids, which are unblended in nature, one is present as a dispersed droplet throughout the other liquid, which is present in a continuous phase. The dispersed droplet is called the internal phase, and the other liquid is the external phase [8,26]. The emulsion is formed with the help of mechanical agitation together with the chemical additives so called surfactant to keep the immiscible liquids being tied together forming one solution. Generally, emulsions are divided into two types: oil-in-water emulsion (O/W) and water-in-oil emulsion (W/O). The O/W emulsion is where the oil is located in the internal phase presented as a dispersed droplet and the water is presented as a continuous phase, whereas for the W/O emulsion, it is the opposite [22]. The O/W emulsion is not suitable to be an alternative fuel. This is due to the large amount of water that might come into direct contact with the cylinder-piston group and fuel feed system, which will result in failure of the fuel combustion [27]. The W/O emulsion fuel is the most suitable and widely used as the alternative fuel for fueling compression ignition engines by researchers and experts. In addition, the type of oil stated earlier refers to the diesel fuel. The water-in-diesel emulsion fuel type is preferable to be the alternative fuel compared to the water-in-gasoline emulsion fuel. This is due to the difference in boiling point between water and diesel fuel being much higher than the one between water and gasoline, which is particularly suitable for the concept [23].

2.1. Emulsion fuel stability and surfactant

The stability of the emulsion produced is very important in order to ensure this alternative fuel can run accordingly in the engine. If the emulsion is destabilized during the engine running time, the probability of the engine failure to operate is high. Plus, it may damage the parts inside the engine. Normally, water-in-diesel emulsion fuel can maintain its stability for up to 3 months [18] but it will depend on various factors, such as the type and percentage of surfactant, the temperature, viscosity, specific gravity and water content [8]. The destabilization process of W/D emulsion fuel will occur after it goes through several phenomena: creaming, aggregation, and coalescence. The creaming process is where the result of the different densities of two phases can be observed. The internal phase either precipitates at the bottom or rises to the surface of the external. For the case of the W/D emulsion fuel, the internal phase, which is the water, will sink to the bottom. Fig. 1 shows the sequence of the creaming phenomena. The aggregation process is where the droplets in the internal phase attract each other. This is due to differences in the polarity of the two phases. As for the coalescence process, it is the final stage of the aggregation process [28]. In a specific view [29], the W/D emulsion fuel starts to destabilize when the repulsive force of the dispersed droplets become weaker; the dispersed droplets, which are located in the internal phase tend to gather towards each other. Thus, they will form bigger droplets, in which the newly formed droplets are separated by a thin film. This process is called the flocculation process. The thin film thickness will reduce due to the attraction of the Van der Waals forces. Then, if the thin film thickness is reduced to a critical value, it will break leading to newly formed droplets to move to each other forming a larger droplet (i.e., Coalescence process). The sequence of the coalescence process is presented in Fig. 2. Consequently, those droplets (water droplets) will settle at the bottom due to the difference in density. This phenomenon is called the sedimentation process. All of these processes will continually destabilize the emulsion until the water and the diesel fuel are fully separated. In addition, the W/D emulsion fuel separation can be initiated by these following cases: low speed environment (the phases after long period will be separated by gravity effect), increase in temperature (lower viscosity), external electric field, high shear stress in the emulsion, the addition of a chemical that influences the emulsifier or liquids, and the addition of a diluting liquid [28].

The presence of a surfactant, sometimes called an emulsifier, is crucial in forming a stable emulsion. The surfactant works as a surface active agent that is a typical chemical additive to attract both the immiscible liquids in forming one stable solution [28]. The surfactant functions by reducing the surface tension of the water by adsorbing at the liquid–gas interface and also reduce the interfacial tension between oil and water by adsorbing at the liquid–liquid inter phase [26]. An alternate perspective is that the surfactant possesses an equal ratio of polar and non-polar portions. As the surfactant blends into the mixture of water and oil, the polar groups of the surfactant orient toward the water and the non-polar group toward the oil, thus lowering the interfacial tension between the two liquids [31]. The surfactant is capable of forming a self-associated cluster, which, generally, leads to organized molecular aggregate assemblies, micelles, vesicles, monolayers, membrane and liposomes [23]. One of the important characteristic of surfactant is the critical micelle concentration (CMC). CMC is defined as the concentration of surfactants above which micelles form and all additional surfactants added to the system go to micelles [32]. Micelle is an aggregate of surfactant molecule dispersed in a liquid colloid where the hydrophobic tails are protected by the hydrophilic head groups. At the CMC point, the surface already becomes saturated and the additional surfactant molecules will not affect the surface tension anymore [33]. There are numerous types of surfactant on the market, which are categorized based on their Hydrophilic-Lipophilic Balance (HLB). A low HLB is generally suitable for forming W/O emulsion and vice versa [8,22]. As for the selection of surfactant for forming W/D emulsion fuel, the surfactant should be free from sulfur and nitrogen and burn easily without soot [23]. In addition, it should not have any impact on the physiochemical properties of the fuel. The surfactants that are most used by researchers and experts are Sorbitanmonooleate, which is called Span 80; Polyoxyethylenenonylphenyl ether, so called Span 80 and Tween 80; Octylphenoxy polyethoxy ethanol or called Triton X-100; Dai-Ichi Kogyo Seiyaku (Solgen and Noigen TDS-30); and liquid soap or glycerin [22]. The percentage of the surfactant being added in the mixture of the unblended fluids is generally between 0.1 and 2%. As the percentage of surfactant is increased further from its maximum value, the stability of the emulsion will deteriorate. This is due to the rapid coalescence that occurs when high surfactant concentration is added [8]. Mechanical agitation plays an important role in helping the surfactant to form a stable emulsion. Common stirring devices used in emulsion studies include – ultrasonic vibration machine, magnetic stirrer, high shear mixer and shaking table [22].

3. Impact of water-in-diesel emulsion fuel on engine performance and emission

Studies of the performance and emission using W/D emulsion fuel are the favorable research areas that, to date, have been extensively investigated by researchers and experts. This is due to the fact that W/D emulsion fuel has a great impact on reducing the emission and improving combustion efficiency. Generally, researchers have analyzed the performance based on the measurement of brake power, torque,

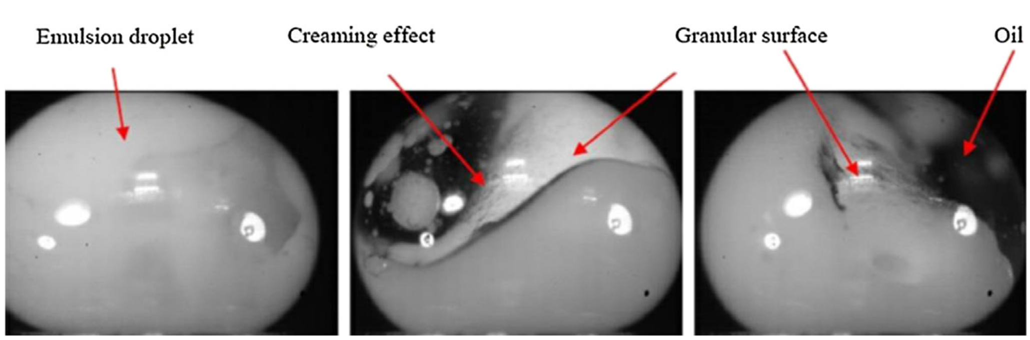

Fig. 1. Sequence of creaming process [30].

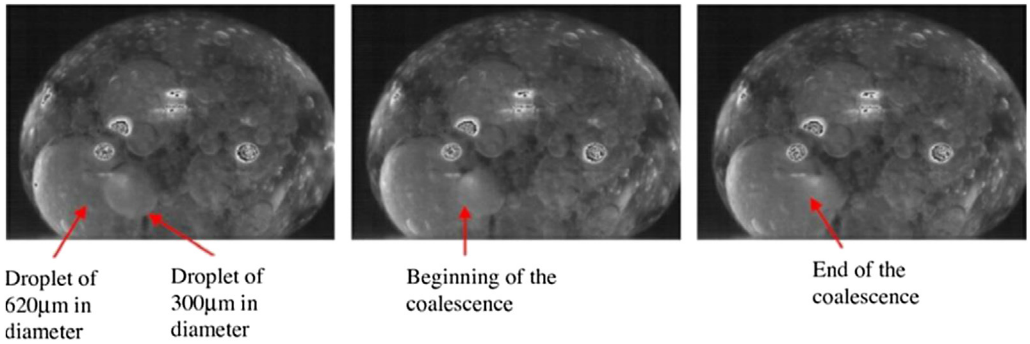

Fig. 2. Sequence of coalescence process [30].

brake thermal efficiency, and brake specific fuel consumption. Instead of using diesel engines, some studies use a burner, bomb experiment and constant volume chamber to observe and analyze the spray, flame and combustion characteristic of using the emulsion fuel. The ignition delay, rate of heat release, and flame lift-off length is also among the favorable subjects of studies to be investigated. As for the emission study, it is analyzed based on the formation of NO_x, PM, HC, CO and smoke emission. The experimental result of the performance and emission of the diesel engine using the emulsion fuel will be reviewed together with the scientific reason of how it affects the engine performance and emission.

3.1. Engine performance

3.1.1. Thermal efficiency

Thermal efficiency is an important study area in analyzing the efficiency and the impact of the tested fuel. From the experimental results reported, most studies found that the thermal efficiency increases when W/D emulsion fuel is used [9,18,25,26,34–38]. Basha et al. [9] found that the thermal efficiency using emulsion fuel is increased to 26.9% compared to neat diesel, which is 25.2%. Others found that the thermal efficiency of using emulsion increases 3.5% from that of neat diesel [38]. Researchers found that there is a strong relation between the ignition delay and micro-explosion phenomena with the improvement of the combustion efficiency. The experimental results indicate that the ignition delay increases by using the W/D emulsion fuel [26,35,39,40]. The effect of increasing the ignition delay is that more diesel fuel can be physically prepared (evaporation and mixing process) for chemical reaction leading to an increase in the rate of heat release and higher fuel burning in the pre-mixed burning. Consequently, more diesel fuel will be consumed and burned. These phenomena will lead to enhanced combustion, and, at the same time, improve the combustion efficiency [25,26,41]. The increase in ignition delay is due to the presence of water in the emulsion. It delays both the physical and chemical ignition process. The presence of water forms latent heat during the vaporization process. Consequently it slows down the rate of the increase in temperature of the droplet. As a result, the physical delay increases. At the same time, the presence of water vapor reduces the fuel concentration, leading to an increase in the chemical delay. Both the chemical and physical delay leads to an increase in the overall ignition delay [39]. The ignition delay normally increases by about 4° crank angle when using the W/D emulsion fuel, while another study found that the ignition delay increases 0.2 ms compared to one of a neat diesel fuel [25]. Although the effect of higher heat release rates is expected to increase the peak temperature, the presence of water in the emulsion causes the temperature to reduce. This is due to the effects of the vaporizing inter phase cooling and dilution process [41]. However, some studies found that the increase in ignition delay leads to an increase in the engine noise [40]. The combustion rate and flame propagation using W/D emulsion fuel is reported to be much faster after ignition compared to that of neat diesel [25]. The other main reason behind the improvement of combustion efficiency and speeding up of the combustion rate when using W/D emulsion fuel is due to the micro-explosion phenomena [18,25,35–38]. During this process, the explosion possesses enough energy to eject torn droplets to a distance of several millimeters away from the spray boundary, breaking them into fine fuel droplets, leading to improved air/fuel mixing, atomization, and evaporation process, thus speeding up the flame propagation [25]. Furthermore, by using W/D emulsion fuel, the flame-lift-off length is reported to be increased [42]. The effect of increased flame-lift-off length allows the fuel and entrained air to be mixed before entering the combustion zone [43]. Consequently, promoting a better mixing process before combustion shall lead to an improvement in the combustion efficiency [42].

3.1.2. Brake power and torque

Although the use of W/D emulsion fuel can improve the combustion efficiency, studies have reported that the brake power and torque are slightly reduced compared to that of neat diesel [11,18,34,40,44]. Many, researchers and experts agree that the reason why there is a slight drop in brake power and torque is due to the fact that W/D emulsion fuel has a lower heating value than a neat diesel fuel, thus less energy is released during combustion [18,34,44]. Some studies explain that this is due to the effect of the ignition delay increment and the maximum pressure rise, which causes the pressure to increase before the top dead center (TDC). Consequently, it will increase the compression work and reduce the network of the cycle leading to a lower power output production [11,40]. However, the difference is relatively low and can be tolerated if compared to the benefit of a huge amount of emission reduction by using emulsion fuel [11]. This is in contrast with the finding of Abu-Zaid [40], who found that brake power and torque increases by using emulsion fuel compared to neat diesel fuel. The author explained that the reason behind the improvement of the brake power is due to the effects of increasing the ignition delay. The fuel that is being injected into the cylinder, undergoing the physical and chemical preparation for combustion, thus helps to reach a higher peak pressure after TDC leading to the production of more power output during the expansion stroke. This is opposite to the explanation provided by other researchers previously. He added that the reason why the torque is increased may be attributed to the

additional force on top of the piston provided by the pressure exerted by the steam. Even though some inconsistent results are reported, when comparing the diesel as total fuel in emulsion with the same amount of neat diesel, it is agreed that the emulsion fuel gives higher brake power and torque due to the its higher combustion efficiency. This also indicates that diesel fuel in emulsion fuel is burned and consumed in more efficient compared to the neat diesel. The percentage of water added to the emulsion fuel may affect the brake power and torque. There are a wide variety of experimental results being reported regarding these studies. Most of the researchers tested 5–40% of water in the emulsion. Alahmer et al. [26] reported that 5% of water added in the emulsion produced the maximum brake power and torque. In addition, he found that 30% of water in the emulsion can be comparable in torque and brake power with 5% and 10% of water in the emulsion. This finding was agreed by another study [45]. Some studies concluded that 20% of water in the emulsion fuel gives the optimum engine performance [38]. Others found that 15–25% of water in the emulsion can obtain the finest engine performance and fuel saving [46]. Although the difference in water percentage may affect the performance as well as the emission of the engine, it cannot be the only factor. Many other factors may affect the experimental result that need to be considered, such as the effect of volatility of the base fuel, ambient temperature, pressure, type of surfactant and engine test condition: engine load, speed, injection timing, compression ratio [34,38,40].

3.1.3. Brake specific fuel consumption

Tsukahara et al. [47] found that by using emulsion fuel, the brake specific fuel consumption (BSFC) shows a remarkable improvement. The same finding was reported in another study [37]. According to Tsuhara et al. [47], the reduction in BSFC may be caused by the following: (1) micro-explosion phenomena, (2) improved air-entraining in the spray due to the increased spray momentum, (3) bigger premixed combustion due to ignition delay, (4) increase in excess of air ratio due to the presence of water in the fuel, (5) reduction in combustion temperature due to the reduction of cooling loss, (6) suppression of thermal dissociation as a result from the reduction of combustion temperature, and (7) more product of combustion gas due to presence of water in the emulsion. Nonetheless, lots of the other experimental results reported that BSFC is slightly increased by using the emulsion fuel as compared to neat diesel [10,18,26,34,48–54]. This is because the calorific value of emulsion is lower than that of the neat diesel fuel [10,18,34,53]. This is because the amount of diesel fuel in emulsion is actually reduced to the equal amount of water added in the emulsion. Thus, it lowers the calorific value of the emulsion [34]. Again, if we compare the diesel fuel in the emulsion as the total fuel with the same amount of neat diesel fuel, the BSFC for using emulsion fuel consumed much less. Abu-Zaid [38] found that the BSFC is reduced when the author compared the diesel fuel in emulsion as total fuel. Fig. 3 shows the BSFC of emulsion by considering diesel and water as total fuel. Fig. 4, on the other hand, displays the BSFC of emulsion by considering diesel as total fuel. For example, in Fig. 3, the 20% of water in emulsion fuel (diesel + surfactant + 20% water) has the highest BSFC compared to that of a neat diesel. When looking at Fig. 4, it is shown clearly that the BSFC is reduced when the diesel is considered as total fuel, especially in the case of the 20% of water in the emulsion fuel. In addition, the reduction of BSFC may be contributed from the effects of the base fuel and water particle size, as it can affect the onset and strength of the micro-explosion [47].

3.2. Exhaust emission

3.2.1. Nitrogen oxide (NO_x)

Most studies reported that the formation of NO_x is greatly reduced when using the W/D emulsion fuel [9,12,26,35,37,48,50,52,54–61]. Some studies found that the formation of NO_x can be reduced by up to 50% [35]. A. Attia and A. Kulchitskiy [61] found that NO_x is reduced to 25% when large size of water droplets is used in the emulsion. Park et al. [54] stated that 20% of water in the emulsion reduces the formation of NO_x by 20%. Others reported that NO_x is decreased by 30% by using 25% of water in emulsion fuel [25,60]. In addition, one study revealed that the reduction of NO_x has a strong relation with the increase in the water percentage [26]. Many researchers agree that the reduction of NO_x when using emulsion fuel is because of the lower peak temperature of the flame during the combustion [9,12,26,39,48,51,56,59]. The reduction of the temperature is due to the high latent heat from the evaporation of water in the emulsion that absorbs the heat during the combustion [48,56]. According to W. Jazair et al. [55], the reduction of NO_x is due to the phase transition of water to steam, which is an endothermic reaction that occurs in the combustion chamber, leading to reduction the in-cylinder temperature. In addition, Farfaletti et al. [51] explained that the combustion temperature is reduced due to the heat sink effect. The water content in the inner phase absorbs the calorific heat value of the emulsion. Consequently, this reduces the burning gas temperature inside the combustion and thus restricts the

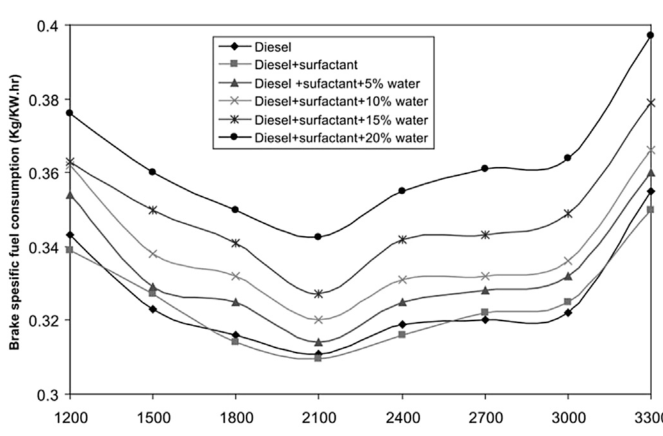

Fig. 3. Brake specific fuel consumption of diesel and emulsion by considering the diesel and water as total fuel [38].

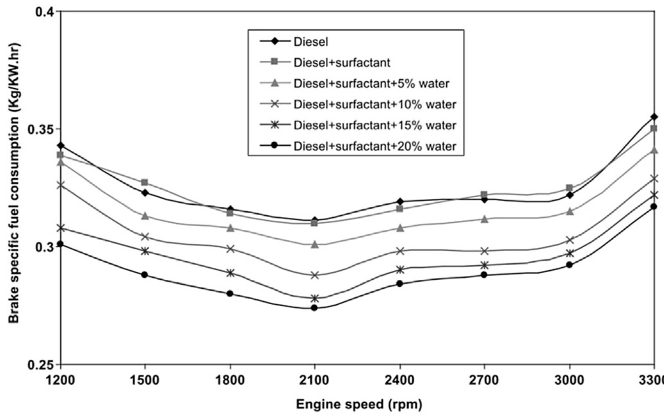

Fig. 4. Brake specific fuel consumption of diesel and emulsion by considering the diesel as total fuel [38].

generation of NO_x. From another perspective, the reduction of NO_x is because of the increase of hydroxyl (OH) radical concentration that is contributed from the presence of water in the emulsion [44]. However, this reason is in contrast to the findings from Ballester et al. [59]. They conducted experiments in investigating the flame of W/D emulsion fuel and neat diesel. The authors measured the spatial distribution in the flame temperature and species concentration (oxygen (O_2), unburnt hydrocarbon (UHC), carbon monoxide (CO) and NO_x). They found that the gas concentration in the inner core of flames during the combustion is very similar between the W/D emulsion fuel and the neat diesel fuel. Figs. 5, 6 and 7 show the spatial concentration of O_2, CO and UHC, respectively, between the W/D emulsion fuel and neat diesel in the inner core of the flame. Those measurements displayed almost similar values for both the emulsion and neat diesel fuel for each type of spatial concentration. Thus, they stress that the reduction of NO_x cannot be attributed to the changes in gas composition. However, they revealed that the reduction of NO_x formation appears in a region where the combustion process is near to completion. The peak flame temperature is located in this area and this flame temperature is reported to decrease 65 K as compared to the neat diesel fuel. This finding proves that there is a strong dependence of thermal-NO formation with the peak flame temperature. Furthermore, one study was conducted in order to investigate the effect of using W/D emulsion fuel on the heat flux crossing the cylinder liner, cylinder head and metal temperature of the injector tip. The findings reported that the presence of water reduces the metal temperature and all heat flux crossing the liner and cylinder head [62].

3.2.2. Soot and particulate matter (PM)

Soot and PM is one of the major indicators of the combustion efficiency [45]. The less formation of these emissions the more efficient the combustion of the tested fuel. From the various experimental results reported, the majority of the studies found that soot and PM are reduced by using the W/D emulsion fuel [24,25,34,37,42,45,48,55,59,60,63–65]. One study reported that the soot emission is reduced to 81% and 89% by using the W/D emulsion fuel and micro-emulsion fuel respectively [64]. Micro-emulsion is the other type of emulsion fuel which has a much smaller dispersed water droplet compared to the normal W/D emulsion fuel. Fig. 8 shows the comparison of soot emission between neat diesel, W/D emulsion fuel and micro-emulsion fuel where the micro-emulsion reduces those emissions the most, followed by W/D emulsion and neat diesel fuel. Many researchers relate the reduction of the soot and PM emission to the better mixing and enhanced atomization caused by micro-explosion phenomena [24,59,63,64]. Some studies reported that the reduction of such emissions is due to the chemical effects. The addition of water in the emulsion augments the concentration of OH radicals, which leads to the oxidation of soot precursors [44]. According to H. Noge, W. Jazair et al. [66], PM reduction tendency would be predicted by light hydrocarbons (LHCs) and polycyclic aromatic hydrocarbons (PAHs) production behavior. Others concluded that the causes of the reduction of those emissions are: lower flame temperature, rapid evaporation of water, decreasing of pyrolysis reaction and the enhanced oxidation of soot precursor due to the addition of OH radicals [64]. In addition, another study reported that the sulfur content in the fuel has a major influence on the formation of PM emission. In normal heavy fuel, approximately 35% of total PM is funded from the sulfates [60]. One study has been conducted, which investigates the morphology of the emission particle samples in order to relate the characteristic of the combustion in the engine. From the photomicrograph of the solid samples collected, the samples appear to be small particles with membranous structure and irregular shapes. This indicates the intense modification of the fuel spray by the disruptive boiling of water droplets and also from the consequences of micro-explosion phenomena during the combustion. The enhanced burnout of the cenosphere, which forms initially in the flame, indicates that the reduction of unburnt carbon emission is 61%.

3.2.3. Carbon monoxide (CO) and unburnt hydrocarbon (UHC)

The formation of CO and UHC emission was reported to increase when using W/D emulsion fuel as compared to neat diesel fuel [45,48,50,52,56,67–69]. However, some study found that the formation of this emission showed slight reduction when using W/D emulsion fuel [20,61] and others reported the values to be of no difference [18]. Kumar et al. [70] found that the UHC and CO emission is reduced when engine using W/D emulsion fuel is tested at the high load range. Researchers relate the reduction of this emission with the effect of micro-explosion process that can lead to complete combustion [20,70]. On the other hand, other researchers explained that the UHC and CO emission is increased due to the lower combustion temperature [48,52]. Furthermore, when the temperature is lower than 1400 K, the oxidation process of CO would freeze. This is due to the presence of water in the emulsion, which leads to the reduction of the flame temperature. Consequently [38], the temperature is not sufficient to convert the CO to carbon dioxide (CO_2) [71]. Another reason is due to the high amount of OH radical contributed from the water, promoting oxidation of carbon to CO [45]. Other than that, some researchers relate the increase of these emissions to the effect of the increase of ignition delay and reduction of flame temperature, which then reduces

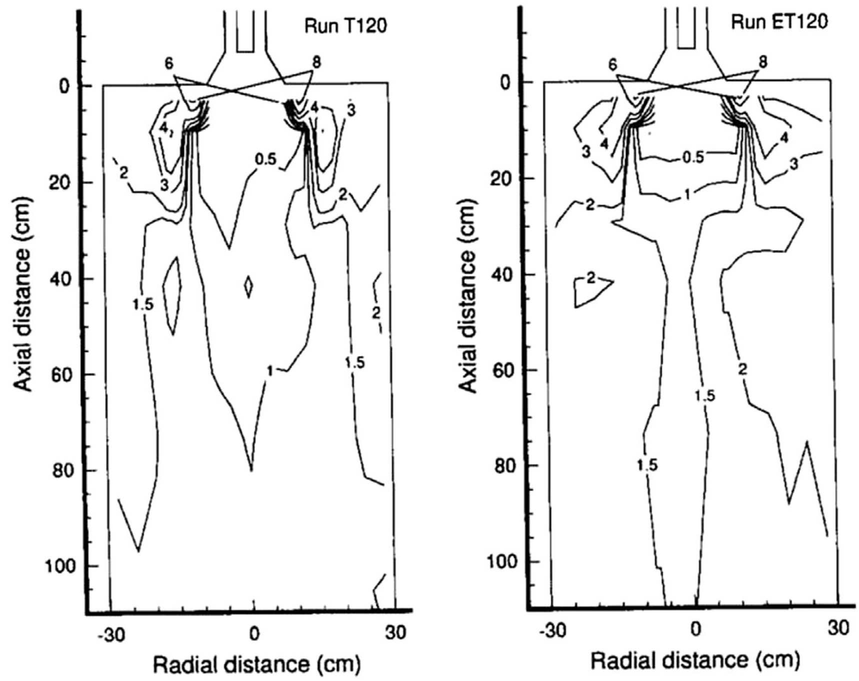

Fig. 5. Spatial distribution of O_2(vol.%, dry basis) for neat diesel (T120) and water in diesel emulsion (ET120) [59].

the combustion efficiency [67]. This is in contrast with most experimental results reported earlier, which state that by using W/D emulsion fuel, the combustion efficiency is increased. Although diverse scientific reasons have been stated, until now, strong evidence and scientific explanation for the inconsistency result of CO and UHC have not been completely revealed.

4. Micro-explosion phenomena

4.1. Fundamental of micro-explosion process

Micro-explosion phenomena have a huge impact on the improvement of combustion efficiency and lower exhaust emission. The micro-explosion process was first discovered by Ivanov and Nevedov [72] in 1965. They reported that the suspended droplets of residual W/O emulsion underwent a spontaneous explosion during the combustion and suggested that this phenomenon be called micro-explosion.

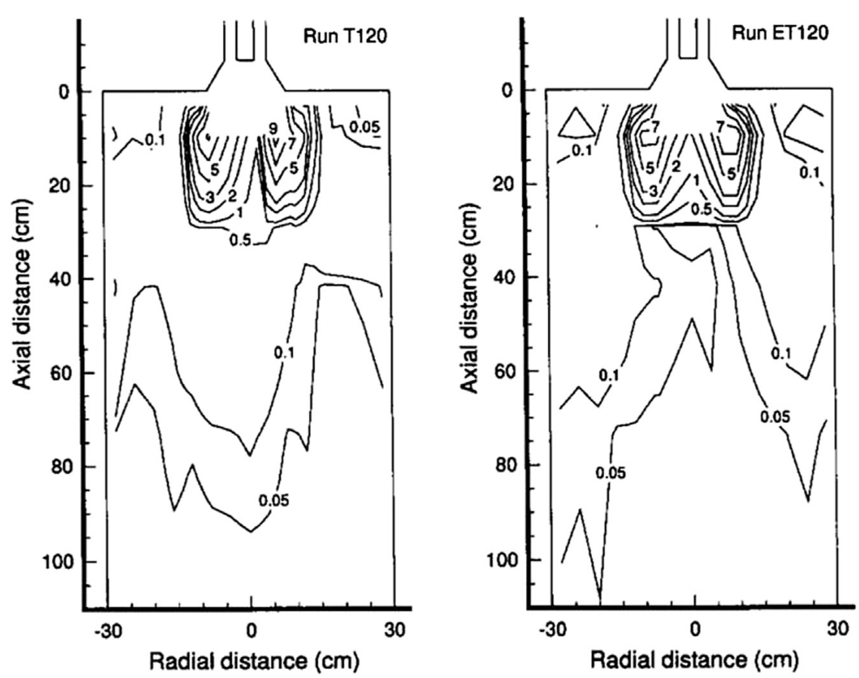

Fig. 6. Spatial distribution of CO (vol.%, dry basis) for neat diesel (T120) and water in diesel emulsion (ET120) [59].

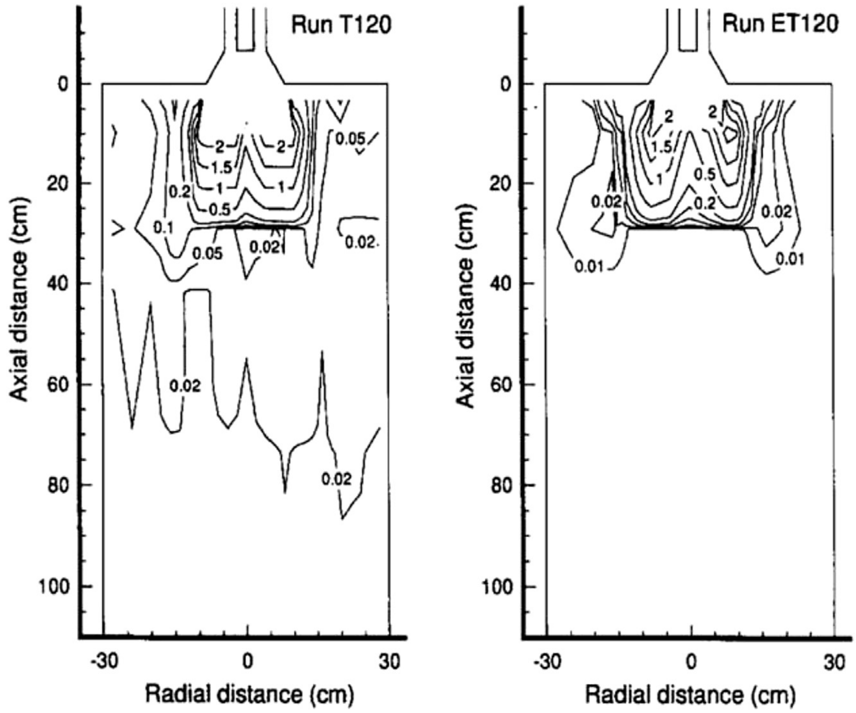

Fig. 7. Spatial distribution of UHC (methane-equivalent vol.% dry basis) for neat diesel (T120) and water in diesel emulsion (ET120) [59].

Subsequently, this phenomenon has attracted considerable research interest worldwide to explore and investigate in more detail. There are a variety of explanations to describe the micro-explosion process. However, all of them reflect the same meaning. Micro-explosion is the secondary atomization of the initial spray as a result of the rapid evaporation process of water that is initially contained in an oil drop [59]. For a specific description, the water in the emulsion fuel is located in an inner phase of the emulsion. As the emulsion fuel is sprayed into a high temperature environment, such as the combustion chamber, the heat will be convected to the surface of the emulsion droplet. However, the volatility and boiling temperature of water and diesel liquids are different in nature. Due to the finite diffusion velocity of a liquid, the diesel fuel will cover the surface of the droplet, surrounding and keeping the dispersed water droplet inside. Once the temperature of the water inside the emulsion droplet reaches to the superheat temperature, rapid bubble nucleation occurs resulting in the expansion and explosion of the whole droplet. Thus, tearing up the droplet into very fine particles [22,24,25,73–77]. Consequently, more surface area of the fine droplets can be exposed to the air leading to an improvement in the fuel and air mixing process. As a result, the

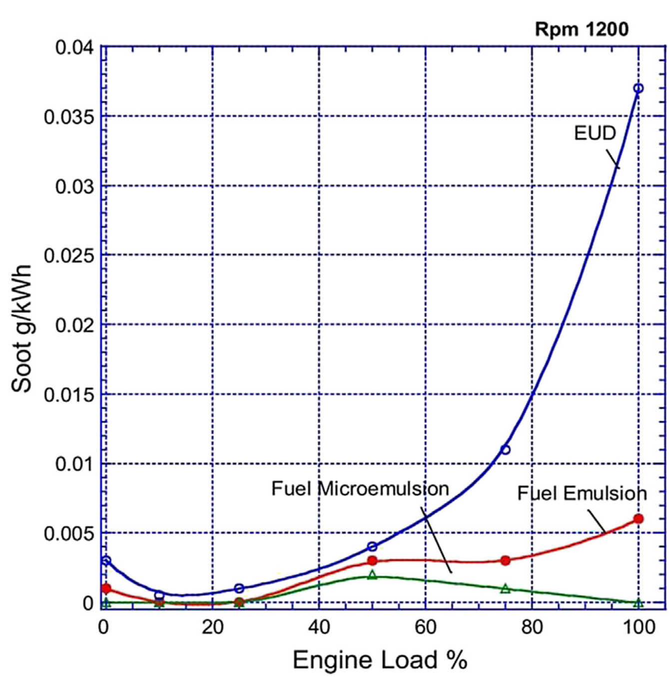

Fig. 8. Comparison of the formation of soot between neat diesel (EUD), W/D emulsion (fuel emulsion) and micro-emulsion fuel [64].

combustion efficiency will increase [77]. Fig. 9 displays the schematic diagram of how the micro-explosion process occurs. According to W.B. Fu [24], the micro-explosion is usually violent due to the great energy storage of the nucleation. Sheng et al. [25] reported that, from their observation of flame characteristics, the flame angle of W/D emulsion fuel is much wider and the flame is much larger than that of neat diesel fuel. This is due to the effect of micro-explosion during the combustion. Furthermore, the presence of glowing spots was observed in the emulsion flame, but unnoticed for neat diesel flame. This is believed to be caused by rapid vaporization of water in the emulsion. The water is expected to rapidly become superheated steam after being introduced into the combustion chamber leading to the occurrence of the micro-explosion [64].

4.2. Current approaches in micro-explosion studies

Numerous studies have been conducted to investigate the micro-explosion phenomena ever since it was first discovered. Different kinds of approaches have been explored by researchers and experts in understanding the occurrence, behavior, and fundamentals of the micro-explosion process. Some studies use the single droplet method to investigate the occurrence of the micro-explosion process [30,73,78,79]. Generally, in the single emulsion droplet method, the droplet is put on a hot plate in which the temperature can be measured and controlled, and then the vaporization process of emulsion and the occurrence of the micro-explosion is captured by a high-speed camera and presented as a shadowgraph. A high speed Charge-Coupled Device (CCD) was used to capture the time resolved shadowgraph of the droplet during heating [30]. One study used different hot plates (stainless steel and aluminum) to determine the evaporation time of the droplet [78]. Instead of using the heating surface technique, Watanabe et al. [73] used the fine wire technique to study the breakup characteristic of the secondary atomization. Fig. 10 shows the schematic diagram of an experimental setup for the fine wire technique. The droplet is suspended from the fine wire and inserted into the electric wall furnace with the temperature wall at 973 K. The onset of micro-explosion was captured by a high speed camera and the thermal history inside the droplet is recorded by the data logger. The fine wire used is a ceramic fiber wire. Mura et al. [80] investigated the micro-explosion process using both techniques; suspended droplet and hot plate (leidenfrost technique); and conducted an experimental comparison between those two methods. They concluded that the quantitative thermal results such as the micro-explosion temperature and the fall temperature after micro-explosion process show the most significant differences. Another study varied the pressure to determine the effect of pressure on the onset of the micro-explosion process [79]. In other research, the effect of multiple droplets arranged in one-dimensional arrays with various droplet spacing, number of droplets and surrounding temperature on the micro-explosion behavior was also explored [76]. The observation of the micro-explosion process in the flame and combustion characteristic is also the favored approach studied by researchers and experts. The occurrence of micro-explosion in the spray flame that was tested in the burner was observed and recorded in the optical system called a simple Mie scatter imaging system and high speed video camera [81]. A study has tested this in the bomb experiments using a high speed multi-pulsed ruby laser holographic camera with image plane optical path [25]. Other than experimental studies, many numerical researches have been conducted, predicting the onset, behavior and strength of the micro-explosion [24,74,82,83]. W.B. Fu et al. [31] modeled a general model of the micro-explosion that predicts the onset and strength of micro-explosion by considering various parameters, such as water percentage, droplet size, dispersed droplet size, and ambient pressure and temperature. In addition, the authors concluded that the general model agreed with the experimental studies. Tarlet et al. [83] setup a numerical model of unsteady heat and mass transfer at the surface and inside of the emulsion droplet, and predict the micro-explosion delay, using homogeneous nucleation hypothesis. Unlike the numerical modeling created by Zeng et al. [82], the numerical model of micro-explosion consists of two parts. The first part addresses the bubble growth, mass and temperature inside the droplet. The subsequent bubble growth leads to the explosion. The bubble generation process is described by the homogeneous nucleation theory. The second part of the model determines when and how the explosion process occurs. The authors claimed that the developed model was first used to study the effects of the various parameters on the onset of micro-explosion after it is validated against the experimental data for bubble growth and homogeneous nucleation.

4.3. Factors influencing the onset and strength of the micro-explosion process

The inconsistency of the experimental findings reported in the previous chapters might be related to the effects of the onset and the strength of the micro-explosion process. The onset of the micro-explosion is defined as the time period from the time fuel is injected until

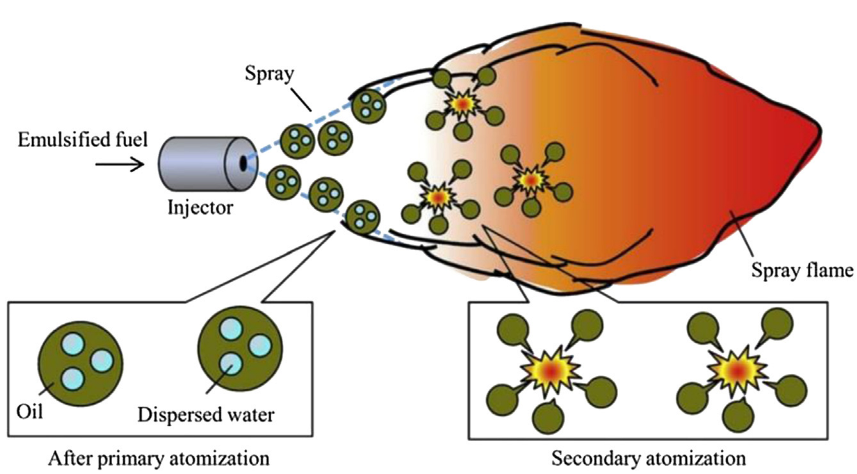

Fig. 9. Schematic diagram of the occurrence of micro-explosion process [73].

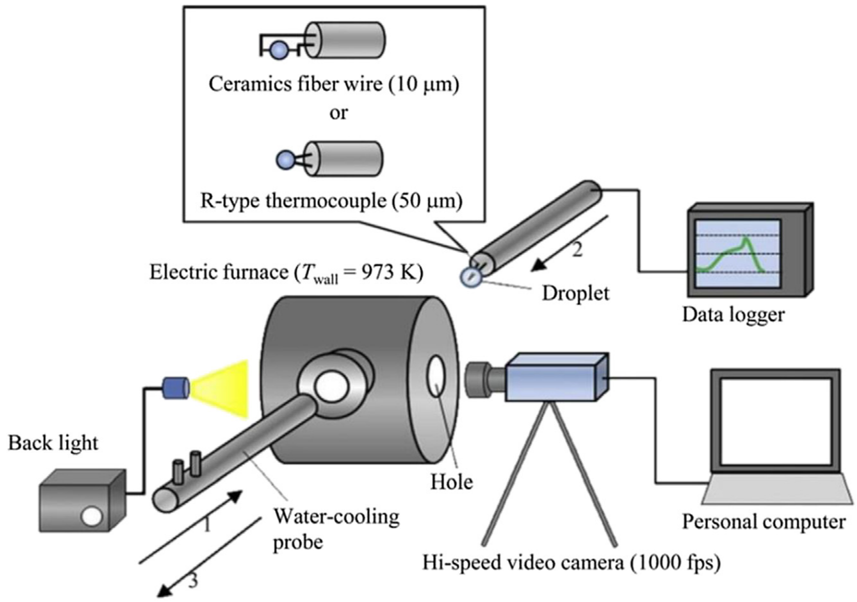

Fig. 10. Schematic diagram of experimental setup for fine wire technique [73].

the micro-explosion starts to occur. Although no measurement can define the strength of the explosion, it is being done by comparing the explosion of the droplet, breaking and ejecting away into fine particles as presented in the shadowgraph. This section discusses the factors that influence the onset and the strength of the micro-explosion process, which can then be correlated to the inconsistent findings reported in the previous chapters.

4.3.1. *Size of dispersed water particle*

The size of the dispersed water particle may affect the strength of the micro-explosion, which has been revealed by many researchers. Nicholas et al. [84] tested different mean water particle sizes of W/O emulsion ranging from 2.1 micron to 4.5 micron. The result shows that the 4.5 micron water particle shows the most crucial explosion. The increasing particle size results in an increase in the ability of emulsified water to disperse the oil droplet. According to the authors, if the water is distributed throughout the oil in very small particles, the droplet only experiences a weak explosion. Plus, only a few fuel fragments are ejected from the primary droplet. Consequently, after the last of the water is evaporated, the droplet still remains but has lost little of its heavy component. This finding agrees with W.B. Fu et al. [24]. From the author's micro-explosion modeling, the strength of micro-explosion is calculated to be weak if the water particle is too small. Plus, only weak expansion and puffing occur. However, the authors stated that, if the particle size is too big, too much water will evaporate, and, thus, insufficient residual water is left. Thus, it will affect the strength of the explosion. Furthermore, Mura et al. [85] reported that from their experimental finding, the optimum dispersed water droplet size is 4.7 microns. After this point, the strength of the explosion begins to fall. Fig. 11 shows the comparison of the explosion by using a different dispersed droplet size. The 4.7 micron meters dispersed droplet size (A) shows a rapid and strong explosion compared to the 17.4 micron meter size (B). In addition, if the dispersed droplet size is too big, the coalescence phenomenon is predominant [30].

4.3.2. *Droplet size of the emulsion*

The droplet size of the emulsion during the spray of fuel into the combustion chamber also influences the strength of micro-explosion. If the initial droplet is too small, the residual water mass is too low or will vanish even before the droplet is heated up to the saturation temperature leading to form a weak micro-explosion [82]. The onset of the micro-explosion process is also affected by the initial emulsion droplet size. With the increased droplet size, the micro-explosion occurs relatively earlier. This is due to the mass fraction difference of the center and the surface, which is larger for bigger droplets. Thus, the superheat region is easier to form, resulting in the micro-explosion occurring relatively earlier [76]. In addition, some studies reported that the micro-explosion will not occur if the droplet is too small due to high difficulty in forming a sufficiently thick oil membrane. Based on the numerical calculation from the micro-explosion modeling, the minimum of droplet size should be at least twice the size of the dispersed droplet [24].

4.3.3. *Water-content in the emulsion*

The percentage of water in the emulsion does have an influence on the onset and the strength of the micro-explosion. From the study reported, if the water content is too small in the emulsion, resulting in less storage energy of nucleation, thus forming weak micro-explosion [24]. From the experiment conducted by Jeong and Lee [76], the authors observed that when the water content in the emulsion is higher, the intensity of the micro-explosion seems to become vigorous and the duration of the explosion is elongated. According to the author, this is due to the flame becoming normal after making a lump when the micro-explosion is finished. However, some studies [25] found that water ranging from 8 to 12% has no significant influence on the violence of the explosion. The authors added that, may be, 8% of water already has enough energy storage to experience micro-explosion. In another study, it is found that the onset and the intensity of the micro-explosion can be enhanced by increasing the water content to a maximum value of 30% [86]. However, in the experiment conducted by Sheng et al. [25], if the water content is too large, it will lead to a negative effect. According to the author, if the initial diameter of the emulsion is held constant, the emulsion with larger water content will lose more water due to the existence of a vortex and no-water layer, leading to lower

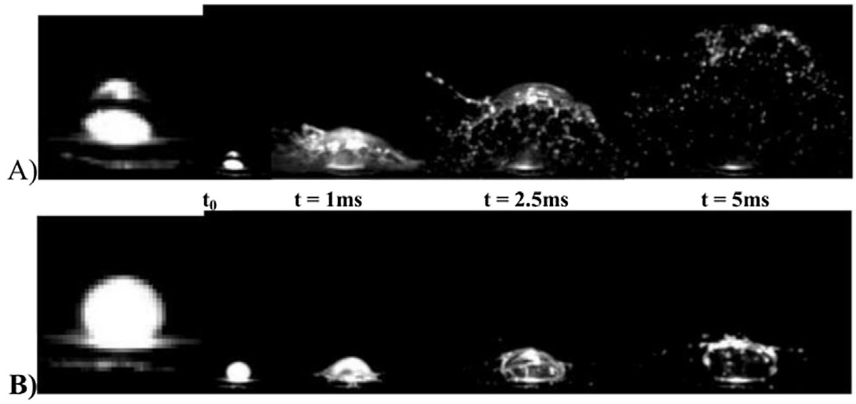

Fig. 11. Sequence of micro-explosion using different dispersed droplet size: (A) 4.7 micron meter, (B) 17.4 micron meter [85].

surface temperature. Furthermore, with large water content in the emulsion, more water evaporation is needed to form an oil membrane, and, consequently, will lead to only a small amount of water remaining in the droplet. This indicates that there is optimum water content in gaining the high energy storage inside the droplet. With the increase in water content to the optimum value, the violence of the micro-explosion can be increased, resulting in smaller fragments and shorter burnout-time after the onset of the micro-explosion [24].

4.3.4. Ambient temperature

According to Watanabe et al. [73], the micro-explosion process is strongly affected by the superheat temperature just before the occurrence of the micro-explosion. Sheng et al. [25] found that the micro-explosion will not occur when the ambient temperature is too low. The author stated that if the ambient temperature is inadequate (733 K in the test) the water, which is located in the internal phase of the emulsion droplet, will evaporate before it reaches the superheated state, thus no micro-explosion can occur. Nonetheless, the author added that if the temperature is too high (823 K in the test), the heat transfer between the droplets and gas is so rapid that the water located near the outer layer will go over the limit of superheat. However, the dispersed water droplet that is located in the center of the emulsion droplet has not yet reached the superheat state. Consequently, the explosion occurs early and only a weak explosion is achieved since the dispersed water droplet inside the emulsion droplet did not explode at the same time. If the ambient temperature is correct (773 K in the test), all the dispersed water droplets inside the emulsion droplet will rapidly exceed the saturation state, superheated state and pseudo-stable state, which leads it to experience the vaporization process and explode at the same time when the dispersed water located near the outer layer reaches the superheat limit. Thus, the vigorous explosion will tear up the droplet and greatly expand the spray volume. In another study [24], it was also found that the effect of ambient temperature speeds up the micro-explosion process. According to the authors, if the temperature is relatively high, the heat flux is larger, leading to the transference of a higher rate of heat transfer, and, hence, leading to a quicker onset of micro-explosion.

4.3.5. Ambient pressure

A few studies have been conducted to investigate the effects of ambient pressure on the micro-explosion process. W.B. Fu et al. [24] reported that pressure has no direct effect on the micro-explosion process. Nevertheless, the authors contended that a higher pressure will increase the boiling point of the heavy component, thus making the micro-explosion easier to occur. The authors added that, as the pressure increases, the solubility of the gas also tends to increase, which then accelerates the occurrence of the micro-explosion. This finding is agreed by Tanaka et al. [79]. From their calculation of the derived formula, they found that the occurrence of the micro-explosion is quicker when the ambient pressure is higher, and with the increase of other factors, such as the saturation temperature of the base fuel, the water content and the surface temperature. However, another study [25] found that an increase in the pressure will make the penetration of the torn droplet much shorter due to the higher gas density. As a result, it will weaken the effect of the explosion.

4.3.6. Others

The type and percentage of surfactant can affect the micro-explosion process. Y. Morozumi and Y. Saito [87] conducted an experiment to investigate the effect of the type and content of emulsifier on the occurrence of the micro-explosion. They found that the micro-explosion temperature and waiting time are affected by those parameters. According to the author, this is due to the thermal decomposition of the emulsifier. However, the increment of the emulsifier from its limits may have a negative effect on the micro-explosion occurrence. The reason is also related to the thermal decomposition of the emulsifier. In addition, the type of diesel engine and engine operating condition may also affect the micro-explosion. As shown in Table 1, the variation of experimental result of NO_x, PM and BSFC when tested in different types of diesel engine, engine operating conditions and water percentage in the emulsion fuel [12]. This factor is also the answer as to why there are many inconsistent experimental results reported. According to one study [25], they found that a 3–5% improvement in engine performance can be achieved by adjusting the engine operating condition. According to their finding, the injection timing should be advanced two degrees of the crank angle to obtain the best average energy saving for emulsion application.

5. Other types of emulsion fuel

Other than the common W/D emulsion fuel, several other types of emulsion fuel have been invented by researchers and/or experts. The main difference is determined by the type and percentage of the chemical additives and the additional processes to produce those emulsions. However, they mainly share the same main substances of a normal emulsion fuel, which are water and diesel fuel.

5.1. Water-in-diesel micro-emulsion fuel

Micro-emulsion fuel was first discovered in 1976 by Gillberg and Friberg [23]. They published a paper on the use of W/D micro-emulsion as a fuel. The term ‘micro’ generally refers to the size of the dispersed droplet in the emulsion. Micro-emulsion has a much smaller dispersed water droplet compared to the normal W/D emulsion fuel. The diameter size of a dispersed droplet in micro-emulsion ranges from 5 to 20 nm compared to W/D emulsion fuel, which ranges from 1 to 10 micron meters. The mean droplet size, which is called the Sauter Mean Diameter (SMD) for micro-emulsion and normal emulsion were determined by the NMR diffusometry to be 12.5 nm and 2.6 micron meters, respectively. The normal emulsion appears to be whitish in color. However, micro-emulsion visually clears as diesel fuel. This is due to the super fine water droplet size in micro-emulsion, which reduces the scatter of light, thus making the emulsion appear like a diesel fuel. The formation of micro-emulsion requires larger amounts of surfactant, normally up to 10%, compared to normal emulsion, which is 2% maximum [64]. One particular company, for example, commercializes a micro-emulsion fuel that contains about 5% water; 12.6% organic oxygenated additives, which consist of glycerine and polyethoxy-ester; and NP-9 surfactant. The heating value of this micro-emulsion is 40.07 MJ/kg (45 MJ/kg for pure diesel fuel) [18]. Micro-emulsion is thermodynamically stable, which is its primary advantage. Unlike the normal emulsion, which is unstable in nature. Nonetheless, this benefit cannot compensate with the drawback of a high percentage surfactant and other chemical additives needed in micro-emulsion formulation. The characteristic difference between the micro-emulsion and normal emulsion is summarized in Fig. 12 [23]. When it comes to comparing the effect of micro-emulsion and normal emulsion in engine performance and emission, not much difference is presented between the two findings. Both emulsions show a high reduction in NO_x and PM compared to neat diesel fuel [8,90]. However, micro-emulsion reduces the gas emissions slightly more than the normal emulsion. In terms of performance, the difference can be detected when the characteristic during the injection of both emulsions is compared. The micro-emulsion penetrates further than normal emulsion during the injection. This is because the micro-emulsion is less volatile compared to the normal emulsion due to the high amount of surfactant added to the emulsion, which leads to a higher reduction in the surface tension of the fluids [64]. Nonetheless, due to the high cost in the formulation of micro-emulsion, it may restrict the commercialization of this emulsion fuel, especially when it requires forming in large scale production.

5.2. Diesel-in-water-in-diesel emulsion fuel

Diesel-in-water-in-diesel emulsion fuel or a 3-phase emulsion is another type of emulsion that has rarely been investigated. Unlike normal emulsion, the physical structure of this 3-phase emulsion consists of an inner, dispersed and outer phase. As shown in Fig. 13, the dispersed phase located in the middle separates the inner and outer phase [49,50]. The dispersed phase will be the water and the inner and outer phases consist of the diesel fuel. Fig. 14 shows the image of 3-phase emulsion captured by using an optical electron microscope at a magnification of 500. Three-phase emulsion has a higher viscosity compared to normal emulsion [24]. The formation of 3-phase emulsion is more complicated than that of normal emulsion and micro-emulsion. There are three common techniques usually used for the formulation of 3-phase emulsion; two-stage emulsification, phase inversion and the mechanical agitation technique. However, the two stage-emulsification process is the technique mostly used. A hydrophilic surfactant is first added to water. Then the mixture of water and surfactant is added to the diesel fuel and is stirred by the homogenizing machine forming a two phase emulsion (denoted as O/W). The O/W emulsion is then mixed with the mixture of diesel fuel and lipophilic surfactant. Again, the newly mixed liquid is stirred by the homogenizing machine, thus forming a 3-phase emulsion [50]. The example of surfactant used in the formation of the 3-phase emulsion is the combination of Span 80 (lipophilic surfactant with HLB = 4.3) and Tween 80 (hydrophilic surfactant with HLB = 15). Little literature is published regarding the investigation of the engine performance and emission using the 3-phase emulsion. Lin and Wang [50] were the first to test the 3-phase emulsion fuel in a diesel engine. They found that the brake specific fuel consumption of 3-phase emulsion is lower than the normal emulsion. In addition, 3-phase emulsion has a higher gas temperature and lower carbon monoxide (CO) and NO_x emission. According to them, the viscosity of 3-phase emulsion is higher than normal emulsion, thus the 3-phase emulsions generated greater unit of volume reaction energy. In addition, due to the different physical structure of 3-phase emulsion as compared to normal emulsion, in which the dispersed water phase is still enveloped by the inner oil droplet in the 3-phase emulsion, it gives a significant impact to the thermal heat release rate and also the micro-explosion strength [50]. In general, the 3-phase emulsion is slightly better in terms of performance and emission compared to the normal emulsion. However, due to the tedious processes and the high cost of forming the 3-phase emulsion fuel, this type of emulsion has not gained much research interest worldwide.

6. Research recommendations

From all the studies that were gathered and discussed in this review, it is clearly shown that the W/D emulsion fuel does have a positive impact on the performance and emission of diesel engines. From when the W/D emulsion fuel was discovered in the 1960s, until the present,

Table 1
Variation of NO_x, PM and BSFC tested on different types of diesel engine, engine operating condition and water percentage in the emulsion fuel [12].

Types of engine and engine operating condition	Water/diesel ratio	NO_x	PM	BSFC	References
One cylinder, light duty, direct injection engine (engine speed = 1250 revolution per minute, engine load = 5 bar (brake mean effective pressure))	0.4	−25%	−20%	+20%	[10]
One cylinder, light duty, direct injection engine (engine speed = 1250 revolution per minute, engine load = 20 bar (brake mean effective pressure))	0.4	−25%	−28%	−10%	[10]
Bus, six cylinders, heavy duty direct injection, EURO 2(MLTB cycle)	0.1	−9%	−20%	+8%	[88]
	0.2	−18%	−43%	+15%	[88]
One cylinder, heavy duty, direct injection (engine speed = 1200 revolution per minute, engine load = 5.2 bar (brake mean effective pressure))	0.5	−40%	−30%	−6%	[89]
Four cylinders, light duty, direct injection. (C100)	0.2	−55%	−45%	+10%	[13]

Emulsion	Microemulsion
Unstable, will eventually separate	Thermodynamically stable
Relatively large droplets (1-10 mm)	Small aggregates (~10 nm)
Relatively static system	Highly dynamic system
Moderately large internal surface, moderate amount of surfactant	High internal surface, high amount of surfactant needed
Small oil/water curvature	The oil/water interfacial film can be highly curved

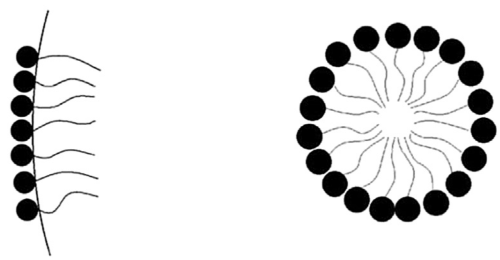

Fig. 12. Characteristic difference between emulsion and micro-emulsion [23].

an enormous amount of studies have been conducted investigating in detail the characteristic, the impact and the behavior of W/D emulsion fuel. However, only limited amount of studies about long term operation using W/D emulsion fuel (durability testing) is shown [65,91]. Friction analysis on piston ring and engine block, carbon deposit on fuel injector, metal debris and water content on lubricating oil and corrosion analysis are the potential research areas that can be investigated after running the engine using W/D emulsion fuel in long period of time. Studies claimed that W/D emulsion fuel is difference with the water injection method where the water is kept inside the fuel droplet, once micro-explosion occurs inside the combustion chamber, the presence of water will be vanished [24,25]. As compared to the water injection method, where the water when introduce into the engine, it tends to direct contact with the engine part, thus resulting negative effect to the engine. Nevertheless, the question remains, is the findings will be the same when test the aforementioned fuel in long period of time?

The stability issue in W/D emulsion fuel is one of its main weaknesses. As discussed earlier in previous chapters, the normal W/D emulsion fuel has its stability period. After exceeding the period, the water and diesel will be separated. Some researchers have already succeeded in forming a thermodynamically stable emulsion (micro-emulsion). However, another issue has come to the fore, which is the price. These alternative fuels are much more expensive compared to neat diesel fuel since they require a high amount of surfactant and other chemical additives, plus they require a tedious process to be completed. Hence, the advantage of using the W/D emulsion fuel does not compensate for the additional price.

There is a possibility of solving emulsion fuel stability issues through mechanical approach. The invention of a fuel production device that requires reduction/without surfactant in the emulsion fuel formation process for example is a good research prospect in solving the stability problem. By going through this approach, the dependence on the high price of surfactant and other chemical additives can be reduced/eliminated. In the 1980s and 1990s, research to invent an emulsion fuel making device was actually a popular research area [92–96]. Different kinds of device were invented and patented. Gerold Kunz [92] patented his invention for an emulsion fuel production device that does not require surfactant, and in which the water-oil ratio can also be manually adjusted. As shown in Fig. 15, water–oil ratios are being adjusted by a dosing apparatus, which is electromagnetically driven by a solenoid. The emulsion fuel will stay stable due to the device working in a closed system that constantly mixes the unused emulsion fuel in the system with the newly made emulsion fuel. A rotary pump functions to ensure that the system constantly circulates and works in a closed system. Other than that, Alfred Kessler [94] patented his design for an emulsion fuel feeding apparatus that also does not require any surfactant. The specialty of this invention is that this emulsion formation device can automatically control the quantity of water based on the combustion parameter inside the engine like combustion pressure, knock and the concentration of emissions. The paper explained that the controlling process of selecting the precise water percentage is based on the engine running condition. From the engine combustion sensor, the system measures the pressure inside the cylinder based on the allowable range of crank angle, and then the data will be stored in the RAM. The system will calculate the suitable water percentage based on the data that is received and transferred to the water charging controller. The selected water percentage is transferred

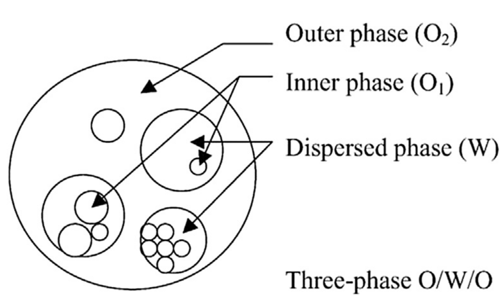

Fig. 13. Physical structure of 3 phase emulsion [50].

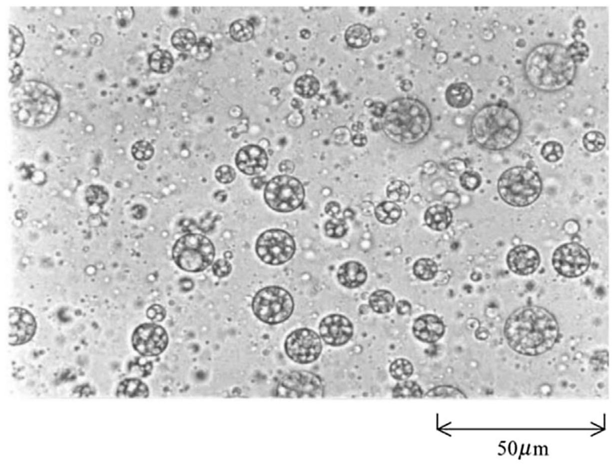

Fig. 14. Photograph of 3 phase emulsion [49].

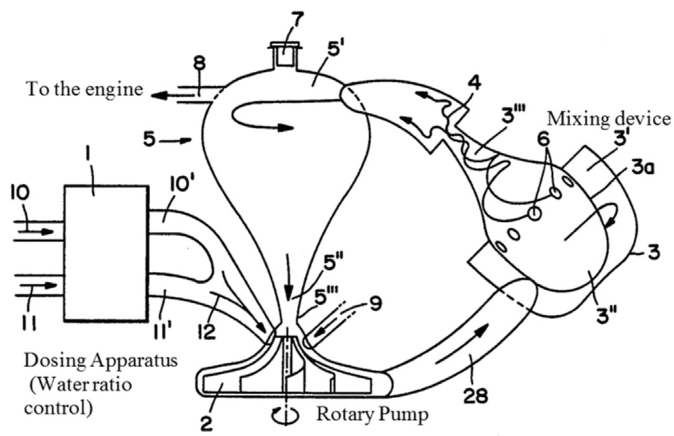

Fig. 15. Emulsion fuel making device [92].

to the emulsion formation device and injected into the diesel engine. Although these devices can solve the W/D emulsion fuel stability issues, the high complexity of the system is a huge barrier in making the commercialization of these devices a reality. However, if the research area of the emulsion fuel studies can be shifted in this direction in future studies, where the focus will be projected in simplifying and optimizing the devices and increasing the efficiency of the mixing method, the barrier of the commercialization issue can be removed. Lemenand et al. [97] and Belkadi et al. [98] are the examples of the recent studies that are working towards this direction. With the advantage of the energy saving and less environmental pollution for W/D emulsion, together with the newly developed emulsion fuel making device, it will provide a great contribution to the industries, and, at the same time, reduce the consumption of energy and ensure less pollution to the environment.

7. Conclusion

The recent advances in W/D emulsion fuel studies that are gathered and reviewed include areas of surfactant, emulsion fuel stability, types of emulsion fuel, emulsion fuel's impact on the performance and emission of diesel engines, and, finally, the micro-explosion phenomenon. From the reviews that were made, it can be concluded that:

1. Thermal efficiency is increased by using the W/D emulsion fuel compared to neat diesel fuel. The majority of the studies agreed that the improvement of the combustion efficiency is due to the increase of ignition delay and the micro-explosion phenomena.
2. It is agreed by most of the studies that W/D does result in improvements in brake power, torque and specific fuel consumption measurements when the total amount of diesel fuel in the emulsion is compared with that of the neat diesel fuel.
3. NO_x and PM emissions are greatly reduced by using the W/D emulsion fuel. The reduction of NO_x is due to the lower peak temperature of the flame during the combustion. PM is reduced due to the effect of the micro-explosion process, which leads to an increase in the combustion efficiency.
4. UHC and CO exhaust emission is found to be increased by using the W/D emulsion fuel. The reason being reported is due to the reduction of combustion efficiency. However, this is in contrast with most experimental results reported that show that the combustion efficiency is increased by using W/D emulsion fuel. Until present, the strong evidence and scientific explanation of the increase of CO and UHC have not yet been completely revealed by researchers and experts.

5. The inconsistency of the experimental results might relate to the effects of the onset and the strength of the micro-explosion process. The factors that affect those measurements consist of the size of the dispersed water particle, droplet size of the emulsion, water-content in the emulsion, ambient temperature, ambient pressure, type and percentage of surfactant, type of diesel engine and engine operating conditions.
6. Durability testing of using W/D emulsion fuel is potential research study that seldom people explored. Friction analysis on piston ring and engine block, carbon deposit on fuel injector, metal debris and water content on lubricating oil and corrosion analysis are the potential research areas that can be investigated after running the engine using W/D emulsion fuel in long period of time
7. The obstacles that slow down the commercialization of emulsion fuel are the high production cost involved and the fuel stability issues. In order to eliminate the barriers to the commercialization of W/D emulsion fuel, simplification and optimization of the fuel production device can be investigated.

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References

[1] S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, et al., IPCC, 2007: Summary for Policymakers, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, United Kingdom, New York, USA, in: Climate Change 2007: The Physical Science Basis, 2007.
[2] T. Barker, Climate Change 2007: An Assessment of the Intergovernmental Panel on Climate Change, 2007, pp. 12–17.
[3] A. Srivastava, R. Prasad, Triglycerides-based diesel fuels, Renew. Sustain Energy Rev. 4 (2000) 111–133.
[4] N. Kumar, U. Khare, Use of macro-emulsion of vegetable oil in compression ignition engine, SAE Pap. (2004) 28–0040.
[5] T. Tan, J. Lu, K. Nie, L. Deng, F. Wang, Biodiesel production with immobilized lipase: a review, Biotechnol. Adv. 28 (2010) 628–634.
[6] K.R. Jegannathan, S. Abang, D. Poncelet, E.S. Chan, P. Ravindra, Production of biodiesel using immobilized lipase—a critical review, Crit. Rev. Biotechnol. 28 (2008) 253–264.
[7] M.S. Kumar, J. Bellettre, M. Tazerout, The use of biofuel emulsions as fuel for diesel engines: a review, Proc. Inst. Mech. Eng. Part A J. Power Energy 223 (2009) 729–742.
[8] M. Nadeem, C. Rangkuti, K. Anuar, M.R.U. Haq, I.B. Tan, S.S. Shah, Diesel engine performance and emission evaluation using emulsified fuels stabilized by conventional and gemini surfactants, Fuel 85 (2006) 2111–2119.
[9] J.S. Basha, R.B. Anand, An experimental study in a CI engine using nanoadditive blended water–diesel emulsion fuel, Int. J. Green Energy 8 (2011) 332–348.
[10] K.A. Subramanian, A. Ramesh, Experimental investigation on the use of water diesel emulsion with oxygen enriched air in a DI diesel engine, SAE Pap. (2001), 2001-01-02.
[11] M.Y.E. Selim, M.T. Ghannam, Performance and engine roughness of a diesel engine running on stabilized water diesel emulsion, SAE Pap. (2007), 2007-24-01.
[12] A. Bertola, R. Li, K. Boulouchos, Influence of water-diesel fuel emulsions and EGR on combustion and exhaust emissions of heavy duty DI-diesel engines equipped with common-rail injection system, SAE Pap. (2003), 2003-01-31.
[13] M.A.A. Nazha, H. Rajakaruna, S.A. Wagstaff, The use of emulsion, water induction and EGR for controlling diesel engine emissions, SAE Pap. (2001), 2001-01-19.
[14] R. Udayakumar, S. Sundaram, S.C. Johnson, Reduction of NO_x emissions by water injection in to the inlet manifold of a DI diesel engine, SAE Pap. (2003), 2003-01-02.
[15] X. Tauzia, A. Maiboom, S.R. Shah, Experimental study of inlet manifold water injection on combustion and emissions of an automotive direct injection Diesel engine, Energy 35 (2010) 3628–3639.
[16] F. Bedford, C. Rutland, P. Dittrich, A. Raab, F. Wirbeleit, Effects of direct water injection on DI diesel engine combustion, SAE Pap. (2000) 1–10, 2000-01-29.
[17] M.A. Psota, W.L. Easley, T.H. Fort, A.M. Mellor, Water injection effects on NO_x emissions for engines utilizing diffusion flame combustion, SAE Pap. (1997), 971657.
[18] W.M. Yang, H. An, S.K. Chou, K.J. Chua, B. Mohan, V. Sivasankaralingam, et al., Impact of emulsion fuel with nano-organic additives on the performance of diesel engine, Appl. Energy (2013).
[19] M. Christensen, B. Johansson, Homogeneous charge compression ignition with water injection, SAE Pap. (1999), 1999-01-01.
[20] M.S. Kumar, J. Bellettre, M. Tazerout, Investigations on a CI engine using animal fat and its emulsions with water and methanol as fuel, SAE Pap. (2005), 2005-01-17.
[21] T. Kadota, H. Yamasaki, Recent advances in the combustion of water fuel emulsion, Prog. Energy Combust. Sci. 28 (2002) 385–404.
[22] F.Y. Hagos, R.A. Aziz a., I.M. Tan, Water-in-diesel Emulsion and its Micro-explosion Phenomenon-review, in: Commun. Softw. Networks (ICCSN), 2011 IEEE 3rd Int. Conf., IEEE, 2011, pp. 314–318.
[23] A. Lif, K. Holmberg, Water-in-diesel emulsions and related systems, Adv. Colloid Interface Sci. 123–126 (2006) 231–239.
[24] W.B. Fu, L.Y. Hou, L. Wang, F.H. Ma, A unified model for the micro-explosion of emulsified droplets of oil and water, Fuel Process Technol. 79 (2002) 107–119.
[25] H. Sheng, L. Chen, C. Wu, The droplet group micro-explosions in W/O diesel fuel emulsion sprays, SAE Pap. (1995), 950855.
[26] A. Alahmer, J. Yamin, A. Sakhrieh, M.A. Hamdan, Engine performance using emulsified diesel fuel, Energy Convers. Manag. 51 (2010) 1708–1713.
[27] V.N. Antonov, Features of preparation of water-fuel emulsions for diesel engines, Chem. Technol. Fuels Oils 19 (1983) 606–609.
[28] J. Schramm, R. Sigvardsen, M. Forman, Bitumen/water emulsions as fuels for high-speed CI engines preliminary investigations, SAE Pap. (2003), 2003-01-31.
[29] P. Sherman, in: P. Becher (Ed.), Encyclopedia of Emulsion Technology, Dekker, New York, 1983.
[30] E. Mura, P. Massoli, C. Josset, K. Loubar, J. Bellettre, Study of the micro-explosion temperature of water in oil emulsion droplets during the Leidenfrost effect, Exp. Therm. Fluid Sci. 43 (2012) 63–70.
[31] J. Jiao, D.J. Burgess, Rheology and stability of water-in-oil-in water multiple emulsions containing Span 83 and Tween 80, AAPS Pharm. Sci 5 (1) (2003) 62–73.
[32] L.-J. Chen, S.-Y. Lin, C.-S. Chern, S.-C. Wu, Critical micelle concentration of mixed surfactant SDS/NP(EO)4o and its role in emulsion polymerization, Colloids Surf. A Physicochem. Eng. Asp. 122 (1997) 161–168.
[33] P. Mukerjee, K.J. Mysels, Critical micelle concentrations of aqueous surfactant systems, Natl. Stand. Ref. Data Ser. 36 (1971).
[34] M.E.A. Fahd, Y. Wenming, P.S. Lee, S.K. Chou, C.R. Yap, Experimental investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition, Appl. Energy 102 (2013) 1042–1049.
[35] B.D. Hsu, Combustion of water-in-diesel emulsion in an experimental medium speed diesel engine, SAE Pap. (1986), 860300.
[36] T. Miyauchi, Y. Mori, T. Yamaguchi, Effect of steam addition on N O formation, Symp. Combust. 18 (1981) 43–51.
[37] T. Murayama, Experimental Reduction of NO_x, smoke, and BSFC in a diesel engine using uniquely produced water, SAE Pap. (1979), 780224.
[38] M. Abu-Zaid, Performance of single cylinder, direct injection diesel engine using water fuel emulsions, Energy Convers. Manag. 45 (2004) 697–705.
[39] H. Transfer, E. Science, An experimental investigation of the burning characteristic of water-oil emulsions, Int. Commun. Heat Mass Transf. 23 (1996) 823–834.
[40] M.Y.E. Selim, M.T. Ghannam, Combustion study of stabilized water-in-diesel fuel emulsion, Energy Sources, Part A Recover Util. Environ. Eff. 32 (2009) 256–274.
[41] Vita A. De, Multi-cylinder D. I. diesel engine tests with unstabiHzed emulsion of water and ethanol in diesel fuel, SAE Pap. (1989), 890450.
[42] J.I. Ghojel, X.-T. Tran, Ignition characteristics of diesel–water emulsion sprays in a constant-volume vessel: effect of injection pressure and water content, Energy Fuels 24 (2010) 3860–3866.
[43] J.E. Dec, A conceptual model of DI diesel combustion based on laser-sheet imaging, SAE Pap. (1997), 970873.
[44] F.L. Dryer, Water addition to practical combustion systems, concepts and application, Symp. Combust. 16 (1976) 279–295.
[45] A.B. Koc, M. Abdullah, Performance and NO_x emissions of a diesel engine fueled with biodiesel-diesel–water nanoemulsions, Fuel Process Technol. 109 (2012) 70–77.
[46] C.W. Coon, Multi-cylinder diesel engine tests with unstabilized water-in-fuel emulsions, SAE Pap. (1981) 21–33, 810250.
[47] M. Tsukahara, Y. Yoshimoto, Influence of emulsified fuel properties on the reduction of BSFC in a diesel engine, SAE Pap. (1989), 891841.
[48] X. Cui, A. Helmantel, V. Golovichev, I. Denbratt, Combustion and emissions in a light-duty diesel engine using diesel-water emulsion and diesel-ethanol blends, SAE Pap. (2009), 2009-01-26.

[49] C.-Y. Lin, K.-H. Wang, The fuel properties of three-phase emulsions as an alternative fuel for diesel engines, Fuel 82 (2003) 1367–1375.
[50] C.-Y. Lin, K.-H. Wang, Diesel engine performance and emission characteristics using three-phase emulsions as fuel, Fuel 83 (2004) 537–545.
[51] A. Farfaletti, C. Astorga, G. Martini, U. Manfredi, A. Mueller, M. Rey, et al., Effect of water/fuel emulsions and a cerium-based combustion improver additive on HD and LD diesel exhaust emissions, Environ. Sci. Technol. 39 (2005) 6792–6799.
[52] K.A. Subramanian, A comparison of water–diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions, Energy Convers. Manag. 52 (2011) 849–857.
[53] K.A. Subramanian, Use of Hydrogen Peroxide to improve the performance and reduce emissions of a CI engine fuelled with water diesel emulsions, SAE Pap. (2008), 2008-01-06.
[54] J.-K. Park, J.-M. Oh, H.-I. Kim, C.-H. Lee, K.-H. Lee, Combustion characteristics of MDO and MDO emulsion in automotive diesel engine, Trans. Korean Soc. Mech. Eng. B 36 (2012) 945–951.
[55] W. Jazair, S. Kubo, M. Takayasu, T. Yatsufusa, Y. Kidoguchi, Performance and emission characteristics of a diesel engine fueled by rapeseed oil bio-fuel, J. Mek. (2011) 32–39.
[56] A. Maiboom, X. Tauzia, NO_x and PM emissions reduction on an automotive HSDI Diesel engine with water-in-diesel emulsion and EGR: an experimental study, Fuel 90 (2011) 3179–3192.
[57] S. Ganesan, A. Ramesh, Investigation on the use of water–diesel emulsion in a L P G – diesel dual fuel engine, SAE Pap. (2001) 223–230, 2001-28-00.
[58] K.P. Duffy, A.M. Mellor, Further developments on a characteristic time model for NO_x emissions from diesel engines, SAE Pap. (1998), 982460.
[59] J.M. Ballester, N. Fueyo, C. Dopazo, Combustion characteristics of heavy oil-water emulsions, Fuel 75 (1996) 695–705.
[60] S. Henningsen, Influence of the fuel injection equipment on NO_x emissions and particulates on a large heavy-duty two-stroke diesel engine operating on water-in-fuel emulsion, SAE Pap. (1994), 941783.
[61] A.M.A. Attia, A.R. Kulchitskiy, Influence of the structure of water-in-fuel emulsion on diesel engine performance, Fuel 116 (2014) 703–708.
[62] M.Y.E. Selim, S.M.S. Elfeky, Effects of diesel/water emulsion on heat flow and thermal loading in a precombustion chamber diesel engine, Appl. Therm. Eng. 21 (2001) 1565–1582.
[63] M.A.A. Nazha, R.J. Crookes, Effect of water content on pollutant formation in a burning spray of water-in-diesel fuel emulsion, Symp. Combust. (1984) 2001–2020.
[64] R. Ochoterena, A. Lif, M. Nydén, S. Andersson, I. Denbratt, Optical studies of spray development and combustion of water-in-diesel emulsion and microemulsion fuels, Fuel 89 (2010) 122–132.
[65] K. Park, I. Kwak, Seungmook Oh, The effect of water emulsified fuel on a motorway – bus diesel engine apparatus and method, KSME Int. J. 18 (2004) 2049–2057.
[66] H. Noge, W. Jazair, Y. Kidoguchi, Y.I. Tajima, Analysis of thermal decomposed components of water emulsified fuel in diesel combustion and effect of the components on PM reduction, Int. Conf. Adv. Mech. Eng. Civ. Eng. (2012) 160–166.
[67] A. Lif, M. Stark, M. Nydén, K. Holmberg, Fuel emulsions and microemulsions based on Fischer–Tropsch diesel, Colloids Surf. A Physicochem. Eng. Asp. 354 (2010) 91–98.
[68] M.S. So, Experimental investigation of the effects of water addition on the exhaust emissions of a naturally aspirated, liquefied-petroleum-gas-fueled engine, Energy Fuels 19 (2005) 1468–1472.
[69] E. Tzirakis, G. Karavalakis, P. Schinas, D. Korres, D. Karonis, S. Stournas, et al., Diesel–water emulsion emissions and performance evaluation in public buses in Attica basin, SAE Pap. (2006), 2006-01-33.
[70] M. Kumar, A. Kerihuel, J. Bellettre, M. Tazerout, Ethanol animal fat emulsions as a diesel engine fuel – part 2: engine test analysis, Fuel 85 (2006) 2646–2652.
[71] John B. Heywood, Internal Combustion Engine Fundamentals, McGraw Hill Book Company, New York, 1988.
[72] V.M. Ivanov, P.I. Nefedov, Experimental investigation of the combustion process in natural and emulsified fuels, NASA Tech. Transl. (1965). TIF-258.
[73] H. Watanabe, Y. Suzuki, T. Harada, Y. Matsushita, H. Aoki, T. Miura, An experimental investigation of the breakup characteristics of secondary atomization of emulsified fuel droplet, Energy 35 (2010) 806–813.
[74] H. Watanabe, Y. Matsushita, H. Aoki, T. Miura, Numerical simulation of emulsified fuel spray combustion with puffing and micro-explosion, Combust. Flame 157 (2010) 839–852.
[75] M. Tsue, H. Yamasaki, T. Kadota, D. Segawa, Effect of gravity on onset of microexplosion for an oil-in-water emulsion droplet, in: Twenty-seventh Symp. Combust. Combust. Inst., 1998, pp. 2587–2593.
[76] I.C. Jeong, K.H. Lee, Auto-ignition and micro-explosion behaviour of droplet array of water-in-fuel emulsion, Int. J. Automot. Technol. 9 (2008) 735–740.
[77] R. Ocampo-Barrera, R. Villasenor, A. Diego-Marin, An experimental study of the effect of water contents on combustion of heavy fuel oil/water emulsion droplets, Combust. Flame 126 (2001) 1845–1855.
[78] M. Abu-Zaid, An experimental study of the evaporation characteristics of emulsified liquid droplets, Heat. Mass Transf. 40 (2004) 737–741.
[79] H. Tanaka, T. Kadota, D. Segawa, S. Nakaya, H. Yamasaki, Effect of ambient pressure on micro-explosion of an emulsion droplet evaporating on a hot surface, JSME Int. J. Ser. B 49 (2006) 1345–1350.
[80] E. Mura, R. Calabria, V. Califano, P. Massoli, J. Bellettre, Emulsion droplet micro-explosion: analysis of two experimental approaches, Exp. Therm. Fluid Sci. (2013) in press.
[81] M. Fuchihata, S. Takeda, T. Ida, Observation of micro-explosions in Spray flames of light oil-water emulsions, Trans. Jpn. Soc. Mech. Eng. B 66 (2000) 1544–1549.
[82] Y. Zeng, C.F. Lee, Modeling droplet breakup processes under micro-explosion conditions, Proc. Combust. Inst. 31 (2007) 2185–2193.
[83] D. Tarlet, J. Bellettre, M. Tazerout, C. Rahmouni, Prediction of micro-explosion delay of emulsified fuel droplets, Int. J. Therm. Sci. 48 (2009) 449–460.
[84] P. Taylor, N.J. Marrone, I.M. Kennedy, F.L. Dryer, Internal phase size effects on combustion of emulsions, Combust. Sci. Technol. 33 (1983) 299–307.
[85] E. Mura, C. Josset, K. Loubar, G. Huchet, J. Bellettre, Effect of dispersed water droplet size in microexplosion phenomenon for water in oil emulsion, Sprays 20 (2010) 791–799.
[86] J.W. Park, K.Y. Huh, K.H. Park, Experimental study on the combustion characteristics of emulsified diesel in a RCEM, in: Seoul. 2000 FISITA World Automot. Congr., 2000, pp. 1–6.
[87] Y. Morozumi, Y. Saito, Effect of physical properties on microexplosion occurrence in water-in-oil emulsion droplets, Energy Fuels 24 (2010) 1854–1859.
[88] A. Barnes, D. Duncan, J. Marshall, A. Psaila, J. Chadderton, A. Eastlake, Evaluation of water-blend fuels in a city bus and an assessment of performance with emission control devices, SAE Pap. (2000), 2000-01-19.
[89] Y. Yoshimoto, Improvement of BSFC by reducing diesel engine cooling losses with emulsified fuel, SAE Pap. (1996) 163–171, 962022.
[90] I. Ahmad, S.R. Gollahalli, Combustion of microemulsion sprays, J. Propuls. Power 10 (1994) 744–746.
[91] http://www.khi.co.jp/english/pressrelease/detail/ba_c3100921_1.html.
[92] G. Kunz, Method of And an Apparatus for Producing a Water-in-oil Emulsion, 4938606, 1990.
[93] R.A. Cemenska, Fuel Emulsion Blending System, 5873916, 1999.
[94] A. Kessler, Emulsion Fuel Feeding Apparatus and Method, 5542379, 1996.
[95] Shimada, et al., Emulsion Fuel Engine, 5245953, 1993.
[96] A. Ulrich, Method and Apparatus Producing a Water-in-fuel Emulsion and Emulsifier Free Water-in-fuel-emulsion, 5125367, 1992.
[97] T. Lemenand, C. Habchi, D. Della Valle, J. Bellettre, H. Peerhossaini, Mass transfer and emulsification by chaotic advection, Int. J. Heat. Mass Transf. 71 (2014) 228–235.
[98] A. Belkadi, D. Tarlet, A. Montillet, J. Bellettre, P. Massoli, Optical diagnostics for W/O emulsification within impinging flow and right angle mini-channel, La Houille Blanche (2013) 52–59.